

Electric-Acoustic Stimulation of Hearing in Adults and Children

Senior Research Thesis

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Abstract

The purpose of this study was to test a possible way of improving speech perception through a cochlear implant, especially for children. Although implants provide a signal that is speech-like, the quality of sound is much different from typical speech. Most deaf listeners have a little low-frequency residual hearing. The idea was explored that perhaps speech perception would be improved by amplifying any residual hearing, even if a small amount, and combining it with the electric signal received through an implant. Three hypotheses were tested. H1: Recognition would be better for a simulated implant signal combined with a low-pass acoustic signal than for the implant simulation alone. H2: Greater benefits would be observed for sentence materials than for isolated words because low-frequency signals provide information primarily about sentence structure. H3: Children would show greater effects than adults because they rely more on the kinds of structure available in the low frequencies. Participants were 20 7-years-olds and 20 adults, all with normal hearing. They identified individual words and sentences with two kinds of processed speech: (1) speech band-pass filtered between 250 and 8000 Hz, and then noise vocoded in four channels, which replicates the signal available through a cochlear implant; and (2) that signal combined with the original signal low-pass filtered below 250 Hz. The results revealed that both children and adults benefitted from the addition of low-frequency information to the vocoded speech for words and sentences. The effect of adding the low-frequency signal was larger for sentences than for individual words. Adults performed better than children in all conditions, but listeners in both groups showed equivalent benefit from the addition of the low-frequency signal. Thus, H1 and H2 were supported, but not H3. Combining acoustic hearing through a high-powered hearing aid with electric hearing through a cochlear implant might enhance speech perception for deaf listeners.

I. Introduction

History of Cochlear Implants

In 1961 Dr. William House's cochlear implant design was first implanted in two patients with hearing loss (Wilson & Dorman 2008). Although many were skeptical about the potential effectiveness of the device, it was an unprecedented achievement in the aspiration to restore hearing to deaf individuals. Ultimately the first archetype of the device failed, but Dr. House continued to research and improve upon his invention (Mahalakshmi & Reddy 2012). Since then cochlear implants have evolved in both sophistication and efficiency in aiding speech understanding.

The first cochlear implant Dr. House developed used a single-channel processor, which provided broad electric stimulation across the cochlea. The single-channel processors were comprised of one cochlear electrode and processed frequencies through a 340-2700 Hz band-pass filter. The strategy used to process the signal was one that relied on replicating the amplitude modulations that occur in the original speech signal. While these preliminary devices were beneficial for aiding lip reading, they were not successful in supporting speech understanding because the processed signal neglected frequency information (Mahalakshmi & Reddy 2012).

It was not until the 1980s that multichannel processor cochlear implants were produced and utilized. The multichannel processors, unlike the single-channel implants, have several electrodes which provide stimulation at multiple locations in the cochlea through the electrode array. The numerous electrodes allow the auditory nerve to be stimulated at different places along the basilar membrane. Additionally, the multichannel processors were receptive to the temporal details and replicated amplitude structure over several frequency bands when

processing the speech signal, which resulted in slightly better spectral resolution (Mahalakshmi & Reddy 2012). The multichannel implants model tonotopic organization to a limited extent in order to code frequencies. The electrodes located at the base of the cochlea respond to high-frequency signal components, whereas the electrodes near the apex of the cochlea are stimulated by low-frequency components (Wilson & Dorman 2008). The electrode array is organized using the filter bank model in which each electrode responds to a specific range of frequencies in the signal and stimulates a specific location along the basilar membrane accordingly. The number of filter bands is dependent on the number of stimulation channels in the device itself (Mahalakshmi & Reddy 2012).

There are three primary strategies for cochlear implant signal processing: waveform, feature-extraction, and hybrid. The waveform strategy for processing relies on the filter bank model to divide the speech signal into specific frequency bands. The amplitude waveform is extracted from each frequency band and each is presented to a different electrode. Originally this approach was vulnerable to interference caused by overlapping of electric fields within the cochlea, which distorted the quality of the signal and reduced speech intelligibility. These technical problems were addressed with the advent of the continuous interleaved sampling (CIS) strategy (Mahalakshmi & Reddy 2012). The CIS strategy is a sequential pulsing in which the electrodes are stimulated intermittently (Wilson & Dorman 2004).

Alternatively, the feature-extraction processing strategy relies on dissecting spectral information, such as fundamental and formant frequencies, from the speech signal. This information is then converted into signals for the electrodes. The detected fundamental frequency is converted into the stimulation rate of the implant. In the first prototypes of the feature-extraction devices, only the fundamental frequency and second formant frequency were extracted

from the speech signal. However, in later models the first formant frequency was added for additional spectral resolution. The formant frequencies are used to determine which electrode is to be stimulated. In models with both F1 and F2, F1 information is used to stimulate apical electrodes and F2 information is used to stimulate basal electrodes. This strategy was highly beneficial in terms of aiding speech recognition because it emphasized features that were common to vowel sounds (Mahalakshmi & Reddy 2012). The feature-extraction method is no longer widely used. Currently, the channel vocoder-type processors are most common in cochlear implant devices (Møller 2006).

Even with the progress the device has made over the last 5 decades, word recognition for implant users remains low. In one study, adult implant users averaged 42% correct for CNC word scores and 72% correct for HINT sentences presented at 70 dB SPL in quiet (Firszt et al. 2004). Although cochlear implants are able to provide a signal that is speech-like in nature to listeners, the quality of sound is much different than the original signal. Currently, cochlear implants typically only deliver high-frequency (above about 300 Hz) electric signals to the user, who in turn loses the benefits of signals displayed at lower frequencies. While these devices have a promising future, it is necessary to explore options that improve speech perception and electric-acoustic stimulation may be one solution. That's where the third processing method comes in: hybrid stimulation. That is the topic of this research project.

Electric-Acoustic Stimulation

There are many ways to combine electric and acoustic stimulation. Both the electric and the acoustic components can be combined into one device, a cochlear implant with a hearing aid on the same ear. This configuration is known as a hybrid cochlear implant. Alternatively, the

electric and acoustic components can be separated into two devices, with a cochlear implant on one ear and a hearing aid in the contralateral ear. That configuration is known as traditional bimodal stimulation. Given that hybrid devices were only recently developed, most of the research available today involves bimodal stimulation (Dorman et al. 2009). As many studies have suggested, the bimodal and hybrid methods of stimulation offer many possible benefits for implant users.

Before the advent of electric-acoustic stimulation, cochlear implant candidacy was limited to patients with slight to no residual hearing. As a result there was little need to explore options of preserving residual hearing, especially since older surgery techniques destroyed any natural hearing with the insertion of the electrode array. However, as technological advances occurred and candidacy requirements changed, so did the ideology surrounding the need to preserve residual hearing.

With the current “soft surgery” technique for cochlear implantation and the design of smaller electrode arrays there is new hope for preserving residual hearing. The gentle insertion of the smaller electrode array into the scala tympani allows for limited damage to the inner ear and the hair cells at the apex of the cochlea. Accordingly, frequencies below roughly 500 to 700 Hz can be utilized with the support of a hearing aid (Dorman et al. 2005). This arrangement is necessary for the hybrid devices. In 2005 Gantz et al. found that around 6 months after implantation with a hybrid device participants scored 69% correct on monosyllabic word recognition. The participants’ scores continued to improve significantly to 79% correct within 6 months to 2 years of implantation (Gantz et al. 2005). This is better than mean scores of patients with only implants, which are closer to 42% correct (Firszt et al. 2004). Although frequencies below 300 Hz are unintelligible when presented alone, they hold crucial information such as

clause structure and intonation within the signal (Büchner et al. 2009). The additive information from the low frequencies expands the spectral range currently covered by cochlear implants, a situation that lends itself to improved speech understanding, especially in noisy conditions (Turner et al. 2004). In 2010 Dorman and Gifford conducted a study which examined the potential benefits of bimodal stimulation in adult cochlear implant patients. They found that the mean word recognition score for the cochlear implant alone condition was 53% correct. For the bimodal condition, participants scored 73% correct. Similarly, when participants were tested on sentence recognition in noise they scored 85% correct in the bimodal condition compared to 40% correct in the cochlear implant alone condition (Dorman & Gifford 2010).

Consequently, there is a potential advantage to combining the high-frequency electrical stimulation of the cochlear implant with the low-frequency acoustic signal of hearing aids. The newest developments in cochlear implant technology have led to a new prospective for the preservation of patient residual hearing. While bimodal stimulation offers users the benefit of the additional low-frequency signal, the overall sound quality may be affected by trying to integrate two diverse signals across ears. Hybrid devices present the signals of the low frequencies from the hearing aid with the high frequencies provided by the cochlear implant to the same ear, so integration should be easier. This method results in a cohesive signal presentation to implant users, which may improve word and sentence recognition. There is now evidence that suggests both methods of electric-acoustic stimulation, bimodal stimulation and hybrid stimulation, are possible. However, the current study used only simulations of conditions involving both signals being presented to both ears. This is similar to hybrid implants.

Hearing Aid Fitting

Traditionally, hearing aids have been fit with low-frequency cut offs around 300 Hz and sometimes as high as 750-800 Hz. The logic behind this practice is to reduce upward spread of masking in hearing aids for users. Upward spread of masking is a phenomenon that occurs when the low-frequency input increases the threshold of the high-frequency signal and it can inhibit speech recognition.

In 1997 Cook, Bacon, and Sammeth conducted a study that examined the effect of reduced low-frequency amplification on speech recognition in noise tasks. Listeners with normal hearing participated. Although the reduction of low-frequency gain was beneficial for the monosyllabic words task in a low-pass noise, this condition is a unique listening environment and is not realistic for everyday hearing aid users. In a more realistic condition, Cook et al. presented speech in broadband noise. Results of that condition revealed there was no improvement in speech recognition with reduced low-frequency gain. This environment is more typical of everyday listening for hearing aid users because this condition involves sentences and noise that is made up of a wide-range of frequencies (Cook et al. 1997).

Other studies that have been conducted involving reduced low-frequency output have been inconsistent with one another. In 1980 Punch and Beck examined hearing aid users' preferences for seven various settings of low-frequency cutoffs. They found that listeners with hearing loss were capable of detecting small differences in low-frequency cutoffs and were inclined to prefer settings with an emphasis in the low frequencies. This study suggested that extending the low-frequency cutoff in hearing aids might provide users with better speech quality (Punch & Beck 1980).

However, in 1984 a study by Tecca and Goldstein showed that hearing aid users' preference for extended low-frequency cut-offs depended on the presentation level of the stimulus. When the presentation level of the stimulus was increased the preference for extended low-frequency output was lessened. By contrast, when the presentation level of the stimulus was decreased, the preference for extended low frequency cut-offs increased (Tecca & Goldstein 1984). The data from these studies illustrate the inconsistency of findings on effects of upward spread of masking with extended low-frequency cutoffs in hearing aids. However, there are many potential benefits of supporting the low-frequency signal for hearing aid and cochlear implant users. Although the present study involves testing frequencies below the typical clinical frequency cutoffs, the work reviewed here shows no evidence to contraindicate modifying traditional fitting settings.

Information Available Through Low-Frequency Hearing

Currently, cochlear implants are typically set to provide only frequencies above 250-300 Hz in the electric signals delivered to the user, who in turn loses the benefits of signals available in lower frequencies. As mentioned previously, low-frequency signals below 300 Hz are unintelligible in isolation. However, the low frequencies may provide crucial information for the listener when paired with the high-frequency signals of the cochlear implant by means of hearing aids. The low-frequency signals contain pitch and information about word parsing, which can help restore some of the integrity to the compromised signal cochlear implant users receive through their device.

In 2010 Zhang, Dorman, and Spahr investigated the impact of low-frequency hearing for cochlear implant users. In that study, they found that when the low-frequency signals were

presented with the signal from the cochlear implant, word recognition scores increased significantly from 56% to 81% on average with the 250 Hz low-passed speech. Similarly, they found that the low-frequency information in combination with the electric signal improved speech recognition of sentences in noise. Without the presence of the low-frequency acoustic stimulation, patients have access to limited spectral information. As a result valuable suprasegmental information available through the lower frequencies is lost (Zhang et al. 2010).

This situation has important implications for a clinical audiologist working with cochlear implant patients. Audiologists base many of their speech comprehension tests for cochlear implant patients on isolated words instead of sentences. Suprasegmental structure should facilitate sentence recognition more than word recognition. One goal of the current study was to determine the potential benefit of testing outcomes of electric-acoustic stimulation with sentence materials rather than isolated words. The hypothesis is that greater benefit may be observed when low frequency acoustic information is combined with higher frequency signals because low-frequency signals provide information primarily about sentence structure.

Bimodal Stimulation in Children

The supplementary information provided by the low frequencies may be especially useful for children with cochlear implants. These children must rely on impoverished electrical signals of speech in order to develop language. This handicap can affect their reading comprehension, reduce academic performance, diminish social well-being, and limit employment opportunities. Therefore it is imperative that alternatives, which improve the recognition attainable with cochlear implants, be explored.

Language acquisition does not simply begin by focusing on isolated consonants and vowels to identify individual words. Rather children must first concentrate on phrase structure and prosody cues in order to understand the structure of their native language. One of the primary linguistic features that infants require in order to facilitate language acquisition is phrasal prosody. Children are particularly sensitive to the changes in pitch, the rhythm and melody of speech, and phrasal boundaries (Christophe, Millotte, Bernal, & Lidz 2008). These critical cues are largely preserved in the low-frequency signals of speech. With this information the infant can process the sentence into distinct parts, which is a process commonly identified as phonological bootstrapping (Morgan & Demuth 1996; Christophe, Millotte, Bernal, & Lidz 2008). Children use the changes in the speaker's fundamental frequency to parse phrases and eventually learn to identify linguistically meaningful units (Nittrouer & Chapman 2009).

In 2009 Nittrouer and Chapman reported that children who had some experience with bimodal stimulation had better generative language skills than children who heard the signal through a single cochlear implant or bilateral implants. These findings suggest that children use the supplementary low-frequency signal to extract information necessary in facilitating speech understanding (Nittrouer & Chapman 2009). As a result, the current study examined the potential benefit for children in the electric-acoustic condition compared to adult participants.

Current Study

Overall the purpose of this study was to test one possible solution of improving speech perception through a cochlear implant, especially for children. In all, three hypotheses were tested. First, the potential advantage was measured for speech recognition with a simulated implant signal combined with a low-pass acoustic signal compared to the implant simulation

alone. Second, the potential benefit for testing with sentence materials than for isolated words because low-frequency signals provide information primarily about sentence structure. Lastly, the study examined the potential for children to show greater effects than adults in the EAS condition because they rely more on the kinds of structure available in the low frequencies. Table 1 shows these hypotheses.

Table 1. Three hypotheses to be tested in the current study.

	<i>Hypotheses</i>	<i>Reasoning</i>
H1	Speech recognition will be greater in the EAS condition than in the VOC condition.	The low-frequency information houses information such as parsing, inflection, and fundamental frequency.
H2	The magnitude of the effect will be greater in whole sentence materials than individual words materials.	Sentence materials may be more appropriate for the types of information available through the low-frequency information.
H3	7-year-olds will show a greater magnitude of the effect than adults.	Children may be more sensitive to the structures available in the low frequencies due to the manner in which they develop language.

II. Methods

Participants

There were 40 participants in this study. These participants were comprised of 20 children, who were 7 years old, and 20 adults. All had normal hearing. They were recruited from fliers sent to local elementary schools and bus advertisements. The participants passed initial screenings of speech proficiency and hearing ability as set criteria for involvement in the study.

The hearing screening consisted of pure tones of the frequencies 0.5, 1, 2, 4, and 6 kHz presented at 25 dB hearing level to each ear separately. The speech screening for children consisted of the Goldman-Fristoe 2 Test of Articulation (Goldman & Fristoe 2000) and the Expressive One-Word Picture Vocabulary Test, 4th Edition (Brownell 2011). Participants were required to score at or better than the 30th percentile for their age on each of these measures. Adults were given the reading subtest of the Wide Range Achievement Test (Wilkinson & Robertson 2006) and the Expressive One-Word Picture Vocabulary Test, 4th Edition (Brownell 2011). These assessments can be used as measures of overall language capabilities and correlate well with speech proficiency. The purpose of these screenings was to establish some measure of uniformity within the group of participants. It was necessary to ensure that incorrect word identification was due solely to an error in perception rather than a phonological process.

Materials

Stimuli were created with custom written software and were administered using Matlab. The stimuli were presented through a Samson headphone amplifier and AKG-K141 headphones in a soundproof booth. The hearing screenings were conducted with a Welch Allyn TM262 audiometer and TDH-39 headphones. Other materials consisted of the computer and software used to present the processed speech. Gameboards with colorful markers were used with children. After each block of test stimuli the children were able to move their token to the next marker on the gameboard and they received a piece of candy or a small toy. SPSS was used to complete the statistical analysis detailed here.

Procedure

This research investigated speech recognition by cochlear implants and hybrid implants using simulation. There was one session held for each subject in the sound-treated audio booth. The participant was asked to complete two tasks involving identifying individual words or sentences through processed speech. There were two conditions being tested in this study. One consisted of vocoded speech only (VOC), with a low frequency cut-off of 250 Hz. This is the standard cut-off for cochlear implants. The other condition consisted of the vocoded speech and the signal below 250 Hz (EAS). The VOC condition represents the electric only stimulation of a cochlear implant, whereas the EAS condition represents the electric-acoustic stimulation of hybrid implants. Vocoded speech can be used as a representation of listening to a signal through a cochlear implant because it reduces a signal's spectral detail in a manner similar to cochlear implants. Vocoded speech is created by dividing a speech signal into 4-channels and then recovering the amplitude envelope. Filtered white noise is then substituted as the carrier signal for the amplitude envelopes to modulate. This results in a signal that has less spectral detail much like the speech presented through a cochlear implant. The software was designed to randomize the order of the presentation of conditions and the initial type of materials for each listener.

During the experiment participants were asked to distinguish the words and sentences they perceived through the headphones. Listeners were provided with practice words and sentences at the beginning of each stimuli block. The sentence materials task had 4 practice sentences, while the individual words tasks had 15 practice words. The purpose of this practice was to familiarize the participants with listening to vocoded speech.

The sentences consisted of four words that were in syntactic order, but were not semantically appropriate. For example, “Old ducks wear tape.” This combination eliminated the possibility for the listener to rely on semantic clues to identify the words. The sentences were scored on the correct number of words recognized in each sentence. Percent correct of word recognition in the sentence presentation served as the dependent variable.

Listeners were also asked to distinguish individual words, which were consonant-vowel-consonant (CVC). The words in this study were selected from Phonetically Balanced Word Lists (Mackersie, Boothroyd & Minniear 2001), which is a list of monosyllabic words that contain the vowels and consonants that occur most frequently in English. The same consonants and vowels are used in each list. The individual words were scored on the number of whole words correct. Percent correct of word recognition in the individual word presentation served as the dependent variable. The test was made up of one set of sentences, which contained 24 sentences, and one sets of words, which contained 80 words in 8 lists of 10 each. Each trial was video recorded and independently scored. Each whole word correct in a CVC word received a score of 1 and each incorrect word received a 0. Sentences were scored in a similar manner, in which a correct word received a score of 1 and an incorrect word received a score of 0.

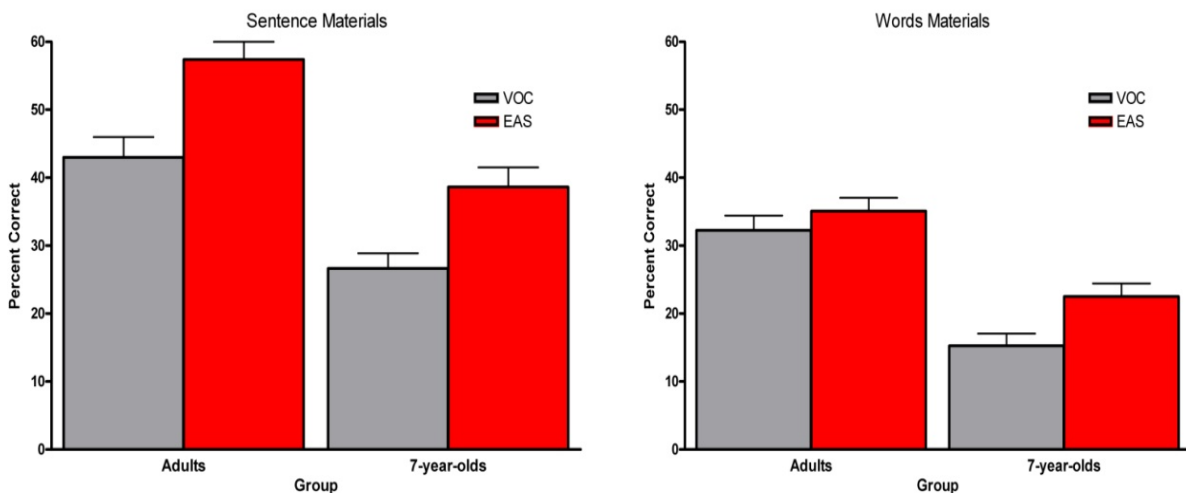
III. Results

External validity. In order to check for external reliability, the outcomes for the conditions that have been used in earlier work were compared to those same conditions in the current experiment. Specifically an earlier experiment in this laboratory tested listeners of the same ages using sentence stimuli in the VOC and EAS conditions. For both adults, and 7-year-

olds, t tests were conducted on recognition scores across experiments. None of the t tests were significant, so it was concluded that these measures were reliable.

Current Study. A 3-way ANOVA was performed with age as the between-subjects factor and materials and processing as the repeated measures to test the three hypotheses posed in the Introduction.

Figure 1. Mean percent correct whole word recognition scores in sentence materials (left) and whole word recognition for individual words (right) for adults and 7-year-olds.



H1: Speech recognition will be greater for the EAS condition than for the VOC condition. The results revealed that in fact speech recognition was greater in the EAS condition than for the VOC condition, $F(1, 38) = 62.17, p < .001$. This means the percent of whole words correct was greater in the EAS condition than the VOC condition in both types of materials and across both age groups. Thus the hypothesis was supported.

H2: The magnitude of the effect for whole sentences would be greater than for individual words. This hypothesis was supported by a significant Materials x Processing interaction, $F(1, 38) = 52.91, p < .001$. While the percent of whole words correct was greater for both the VOC and EAS conditions in the sentence materials, there was a much greater benefit of the added low-frequency signal in the sentence materials.

H3: Seven-year-olds will show a greater magnitude of the effect than adults. The results revealed that adults performed better in both EAS and VOC conditions and on both types of materials than children, as shown by the significant age effect, $F(1, 38) = 62.17, p < .001$. The magnitude of the effect was expected to be greater for children than for adults. However, this hypothesis was rejected because the Age x Processing and the Age x Materials interactions were not significant. Overall, adults performed better than children in all conditions, but listeners in both groups showed equivalent benefit from the addition of the low-frequency signal. Therefore combining acoustic hearing through a high-powered hearing aid with electric hearing through a cochlear implant might enhance speech perception for deaf listeners.

IV. Discussions:

Results revealed that both children and adults benefitted from the addition of low-frequency information to the vocoded speech for words and sentences. The current study emphasizes the importance of improving speech recognition through cochlear implants by electric-acoustic stimulation, particularly for children. Children with hearing loss are straddled with the burden of acquiring language through an implant, which provides a signal that is vastly different to what a normally functioning cochlea produces. As a result speech production and language proficiency are often negatively affected. It is not enough to focus only on ways to

amplify the signal to individuals with hearing loss; the quality of the signal must also be improved.

It is also important to recognize that the effect of adding the low-frequency signal was larger for sentences than for individual words. Traditionally audiologists have used individual word materials to gauge speech perception for patients with cochlear implants. As demonstrated by the materials effect, sentence task materials may be a more appropriate measure of speech recognition for implant recipients. Also, sentence materials are more realistic to the stimuli individuals with implants experience when conversing with others. With the addition of the acoustic signal, speech recognition increased significantly when compared to the vocoded alone condition in sentence materials.

Although EAS has been shown to provide benefit for both adults and children, hybrid implants are currently still in clinical trials. This study has potentially significant implications for the fields of audiology, otolaryngology, and aural surgery. With more research and publicity hybrid implants can become the standard for cochlear implant candidates.

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